Crossing Phenomena in Overhead Line Equipment (OHLE) Structure in 3D Space Considering Soil-Structure Interaction

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Crossing Phenomena in Overhead Line Equipment (OHLE) Structure in 3D Space Considering Soil-Structure Interaction

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Abstract. Nowadays, the electric train becomes one of the efficient railway systems that are lighter, cleaner, quieter, cheaper and faster than a conventional train. Overhead line equipment (OHLE), which supplies electric power to the trains, is designed on the principle of overhead wires placed over the railway track. The OHLE is supported by mast structure which located at the lineside along the track. Normally, mast structure is a steel column or truss structure which supports the overhead wire carrying the power. Due to the running train and severe periodic force, such as an earthquake, in surrounding area may cause damage to the OHLE structure especially mast structure which leads to the failure of the electrical system. The mast structure needs to be discussed in order to resist the random forces. Due to the vibration effect, the natural frequencies of the structure are necessary. This is because when the external applied force occurs within a range of frequency of the structure, resonance effect can be expected which lead to the large oscillations and deflections. The natural frequency of a system is dependent only on the stiffness of the structure and the mass which participates with the structure, including self-weight. The modal analysis is used in order to calculate the mode shapes and natural frequencies of the mast structure during free vibration. A mast structure with varying rotational soil stiffness is used to observe the influence of soil-structure action. It is common to use finite element analysis to perform a modal analysis. This paper presents the fundamental mode shapes, natural frequencies and crossing phenomena of three-dimensional mast structure considering soil-structure interaction. The sensitivity of mode shapes to the variation of soil-structure interaction is discussed. The outcome of this study will improve the understanding of the fundamental dynamic behaviour of the mast structure which supports the OHLE. Moreover, this study will be a recommendation for the structural engineer to associate with the behaviour of mast structure during vibration.

1. Introduction

Over the time, the passenger journeys have increased by nearly 100% and freight by 60%. The provided extra capacity is needed for the economic growth in the future [1]. The electric train becomes one of the efficient railway systems. This train is allowed to run more frequently and quickly. Also, electric train are more comfortable and environmentally superior. Although the train are vibrated less due to the absence of diesel engines, the train and their equipment might be experienced the vibration due to the environmental event.

Overhead line equipment (also called "OHLE") is an equipment to supply power to make electric trains move. OHLE, consist of masts, gantries, and wires found along electrified railways, is now the preferred means of powering trains throughout the world. Although the concept of OHLE is simple, the problem is a poor dynamic behaviour of OHLE are needed to develop [2]. Mast structure, which is a slender column, should be observed due to the vibration.

Due to the running train and severe periodic force, such as an earthquake, in surrounding area may cause damage to the track and OHLE structure especially mast structure which leads to the failure of the electrical system [3-6]. This is because when the frequency of ground motion matches the natural frequency of a structure. It will suffer the damage and large oscillations because of the occurrence of resonance effect [7]. In practice, the support condition of masts is designed as a fixed support with infinity stiffness. In reality, there is a small displacement created by the supporting soil. Based on the revealed literature [8,9], difference soil support conditions are taken into account. It is noted that soil-structure interaction affects the overall response of the structure. The variations of rotational stiffness are taken into account to understand the dynamic behaviour. Then, modal crossover phenomena are expected when one of the mode shape curves intersect another and the dynamics behaviour is characterized by coincident eigenfrequencies, mode order change, while the eigenfunctions remain associated with the corresponding eigenvalues [10-12]. This will occur when the structure vibrates within the frequencies range that combines more than one mode of vibration. Then, the mode of vibration cannot be predicted due to the crossing phenomena.

This paper aims to study the dynamic behaviour of overhead line equipment. Also, the influences of soil stiffness are considered. The outcome of this study will improve the understanding of the fundamental dynamic behaviour of mast structure which supports the OHLE with consideration of its underlying soil properties. Moreover, this study will be a recommendation for the structural engineer to associate with the behavior of mast structure during vibration.

2. Finite element simulation

In this study, the 3-dimensional finite element modelling is considered using a general-purpose finite element package STRAND7 [13]. OHLE is normally supported from lineside masts, typically made of H-section, with a fixed base. The catenary cable and the pull/push-off arms supporting the contact wire are attached to the ends of the cantilever. The modelling of mast structure is shown in figure 1, where consist of the two force member only.

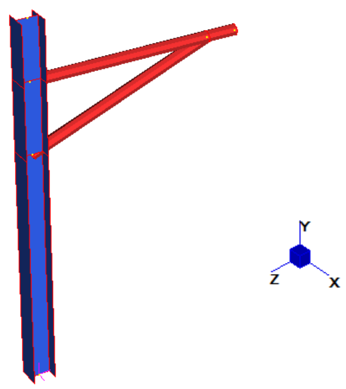


Figure 1. 3-Dimensional model of OHLE

The mast structure is a column using wide flange and the cantilever is a round hollow structural section (HSS). The young modulus of steel is $2x10^5$ MPa with the density of 7850 kg/m^3. Poisson's ratio is 0.25.

2.1 Calculation of spring stiffness
2.1.1 Stiffness of horizontal spring
The widely used of analysis is using Winkler model [14] to represent the horizontal stiffness as shown in Equation 1.

$$k_h = p/y \tag{1}$$

Where p = lateral pressure, y =deflection
Also, Davisson [15] present the modulus of subgrade reaction for clay as shown in Equation 2.

$$k_h = 67S_u/B \tag{2}$$

Where S_u = undrained shear strength, B = width or diameter of the pile

2.1.2 Stiffness of vertical spring
The axial stiffness is used as vertical spring stiffness. The cross sectional area, length and modulus of elasticity of pile are considered as shown in Equation 3.

$$K_v = EA/L \tag{3}$$

Where E = modulus of elasticity of pile, A = cross sectional area of pile, and L = length of pile

2.1.3 Stiffness of rotational and torsional spring
The rotational stiffness is the relationship between applied moment and rotation as in Equation 4.

$$k = M/\theta \tag{4}$$

Where M= applied moment, θ=rotation
As for the torsional stiffness, the relationship between shear modulus, torsion constant and length of pile are considered as shown in Equation 5.

$$k = GJ/L \tag{5}$$

Where G = shear modulus, J = torsional constant, and L = length of pile

In this study, the translational stiffness in three directions is assumed to be fixed in order to restraint the translation displacement. Based on soil conditions, although, translational stiffness is not taken into account, soil springs with varying rotational stiffness from very small values (nearly unstable) to infinity (fully fixed support) are considered in order to understand the effect of soil-structure interaction on the mode of vibration of OHLE.

3. Results and discussion
Table 1 shows the mode shape of mast structure with the fully fixed support conditions in the first ten modes. There are 4 modes in twisting, 3 modes in bending about x-axis and 3 modes in bending about z-axis. The first mode of vibration presents the first twisting mode, while the second and fifth mode shows the first and second mode of bending about x-axis. The third and fourth mode represents the first and second mode of bending about z-axis, respectively.

Table 1. Mode shape and natural frequencies of mast structure

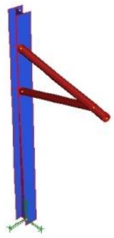
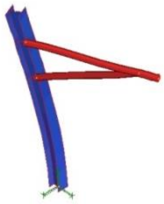
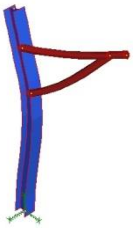
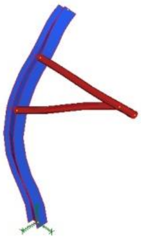
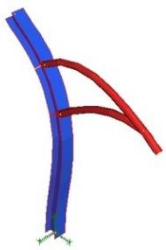
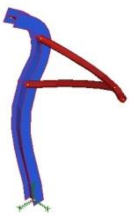
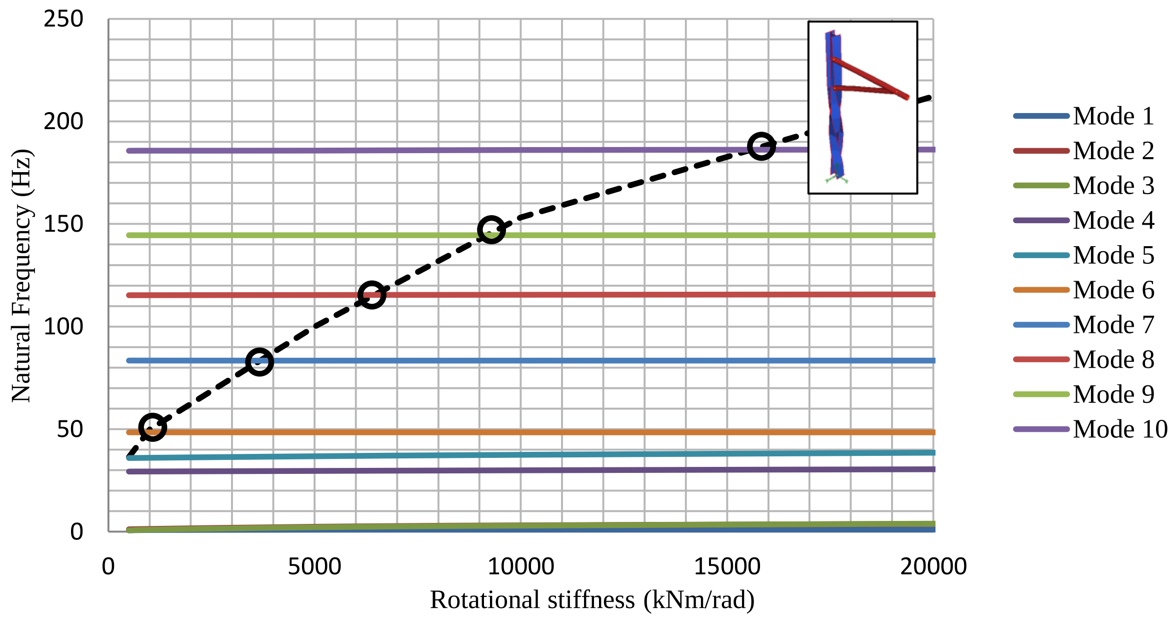
Mode	Mode shape and natural frequency (Hz)	Mode	Mode shape and natural frequency (Hz)
1	 1.07 (1^{st} twisting)	2	 5.63 (1^{st} bending abt x-axis)
3	 7.76 (1^{st} bending abt z-axis)	4	 35.04 (2^{nd} bending abt z-axis)
5	 42.63 (2^{nd} bending abt x-axis)	6	 48.46 (2^{nd} twisting)
7	 83.43 (3^{rd} twisting)	8	 117.4 (3^{rd} bending abt z-axis)
9	 144.52 (3^{rd} twisting)	10	 188.64(3^{rd} bending abt x-axis)

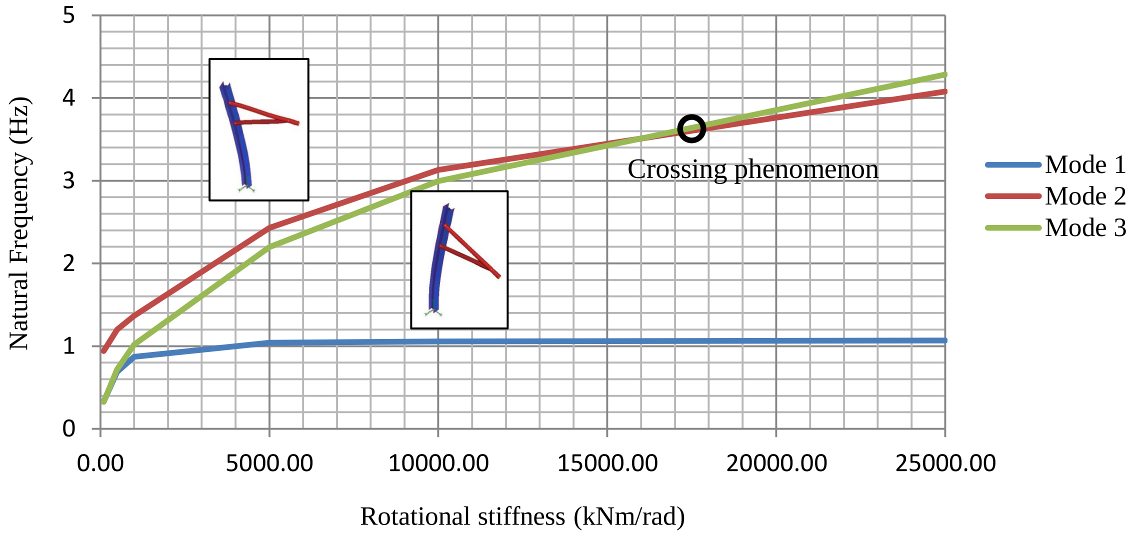
Table 2. Dynamic behavior of Mast structure with varying rotational stiffness

Mode no.	Resonance (Hz)					
	K= 100	K= 1000	K=10000	K=100000	K=1000000	Fully Fixed
1	0.33	0.87	1.06	1.07	1.07	1.07
2	0.94	1.37	3.13	5.08	5.57	5.60
3	0.32	1.02	2.99	6.20	7.55	7.65
4	29.32	29.39	29.95	32.51	34.62	34.82
5	35.86	36.05	37.51	41.04	42.43	42.53
6	48.46	48.46	48.46	48.46	48.46	48.46
7	83.44	83.44	83.42	83.43	83.43	83.43
8	115.28	115.30	115.50	116.43	117.26	117.35
9	144.52	144.52	144.52	144.52	144.52	144.52
10	185.69	185.77	186.35	187.89	188.54	188.59

Table 2 and Figure 2 show the influences of rotational stiffness on natural frequencies of mast structure. The first ten modes of vibration is observed. It can be clearly seen that the natural frequencies remain nearly constant or decrease gradually in a higher mode. This is because the rotational stiffness of soil does not affect the natural frequencies a in higher mode of vibrations. However, mode 20, which is a twist mode between the support and the lower cantilever member when the supports are fixed, is noticeable that the frequency changes significantly to less than 50 Hz when the rotational stiffness decreases to about 1000 kNm/rad. The 5 crossover phenomena by this mode can be observed as shown in figure 2a. In general, it should be noted that the occurrence of this twist mode shape is an unexpected shape. It is interesting that the dynamic behavior of mast structure should be investigated in depth for further research. In term of lower mode of vibrations, the effect from soil-structure interaction can be observed. From table 2 and figure 2b, it is interesting to note that when the stiffness is reduced to 10000 kNm/rad, the frequency of the 1st bending about x-axis (mode 2) become greater than the 1st bending mode about z-axis (mode 3). Crossing phenomenon is observed at the point which the structure has a rotational stiffness around 17000 kNm/rad. There is a crossover between mode 2 and 3 at 3.5 Hz.



a)



b)

Figure 2. Crossing phenomena in mode of vibration of mast structure

4. Conclusions

Overhead line equipment (OHLE), which supplies electric power to the trains, is designed on the principle of overhead wires placed over the railway track. The OHLE is supported by mast structure which located at the lineside along the track. In general, mast structure is a slender column. Due to the running train and severe periodic force, such as an earthquake, in surrounding area may cause damage to the OHLE structure especially mast structure which leads to the failure of the electrical system. In addition, when the structure vibrate within the frequency range which match the frequency of ground motion, the resonance effect occurs and will amplify the effects of a ground motion, causing a structure to suffer more oscillation and damage. In this study, modal analysis is discussed in order to simulate natural frequency and mode shape of vibration. In practical work, the structures are designed with the assumption of having fixed support. In reality, there is a small displacement created by the supporting soil. Hence, three-dimensional mast structure is created using finite element package STRAND7 with the consideration of soil-structure interaction. This paper presents the relationship between natural frequencies and rotational stiffness of soil spring. Based on the obtained results, it is noticeable that the rotational stiffness rarely affects the natural frequencies and mode shape in a higher mode. However, crossing phenomena are suspected by an unexpected twist mode (mode 20). As for lower frequencies, it is clearly seen that 1^{st} mode of bending about x-axis intersect with 1^{st} mode of bending about z-axis at 3.5 Hz. Nevertheless, it is recommended to do further study on different mast structure with more slenderness ratio in order to observe more crossing and veering phenomena. The outcome of this study will improve the understanding of the fundamental dynamic behavior of the mast structure considering soil-structure interaction which supports the OHLE. Moreover, this study will be a recommendation for the structural engineer to associate with the behavior of mast structure during vibration.

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